Spectroscopic study of Kaonic nuclei using inclusive and exclusive $^{12}C(K^-, p)$ reaction at J-PARC

Fumiya OURA

(Tohoku University, Japan)

for the J-PARC E42 collaboration

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Outline

- $\overline{K}N$ interaction and $\overline{K}$-nucleon bound system
- Kaonic nucleus search via inclusive $^{12}\mathrm{C}(K^-, p)$ reaction
  - Result: optical potential
  - Result: event excess
- New attempt of exclusive search with TPC at J-PARC (E42 experiment)
  - Experimental setup
  - Basic analysis
  - Result: missing mass resolution of $p(K^-, p)$ reaction
  - Result: inclusive spectrum of $^{12}\mathrm{C}(K^-, p)$ reaction
  - Result: exclusive spectrum with request for tracks in TPC
- Summary

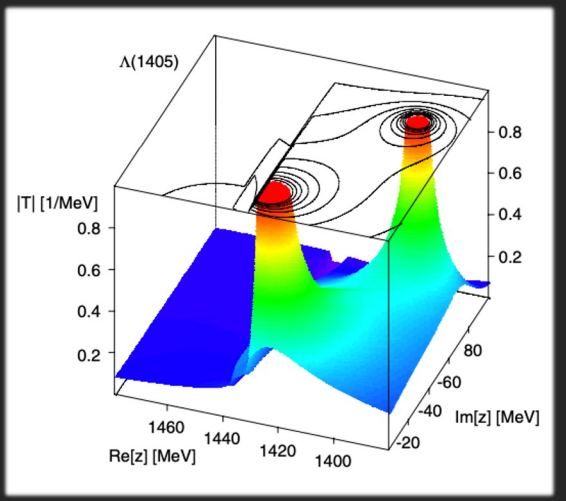
Introduction

$\bar{K}N$ interaction & $\bar{K}$-nulceon bound system

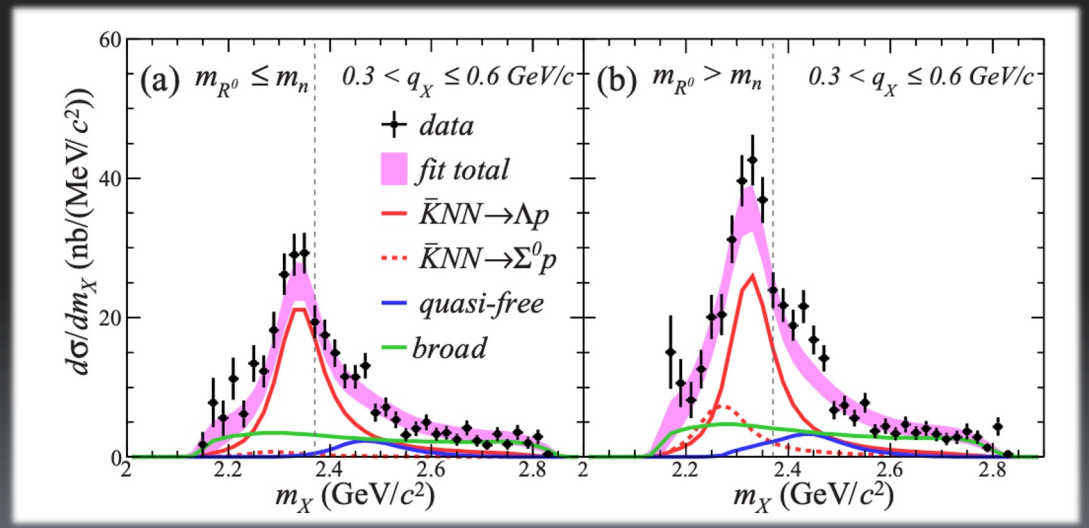
- $\bar{K}N$ (I=0) attractive interaction results in $\Lambda^*(1405)$? [1]

- $\bar{K}NN$ state search (J-PARC E15) [2]
  - Clear bump structure in invariant mass *via* $^3\mathrm{He}(K^-, \Lambda p)n$
  - Lightest kaonic nucleus
  - $B_K = 42 \pm 3\ ^{+3}_{-4}$ MeV / $\Gamma = 100 \pm 7\ ^{+19}_{-9}$ MeV
  - Due to $\bar{K}N$ and Λ^*N attraction?

[1] T. Hyodo, D. Jido
Prog. Part. Nucl. Phys., **67**,
021D01 (2015)



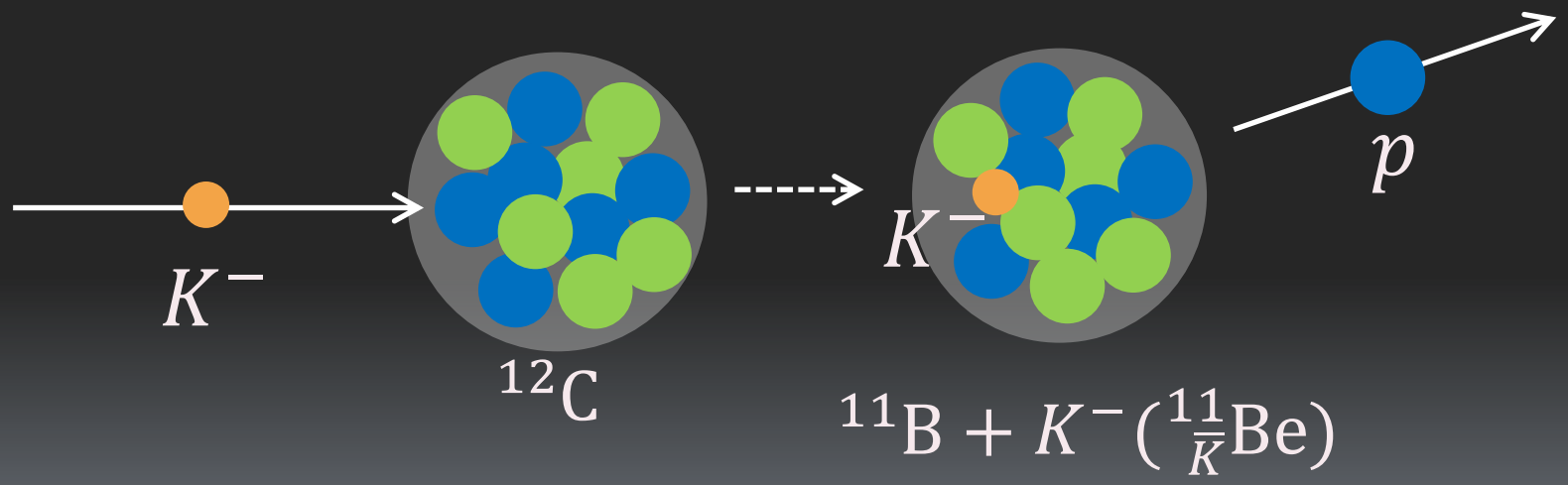
[2] T. Yamaga *et al.*
Phys. Rev. C **102**,
044002 (2020)

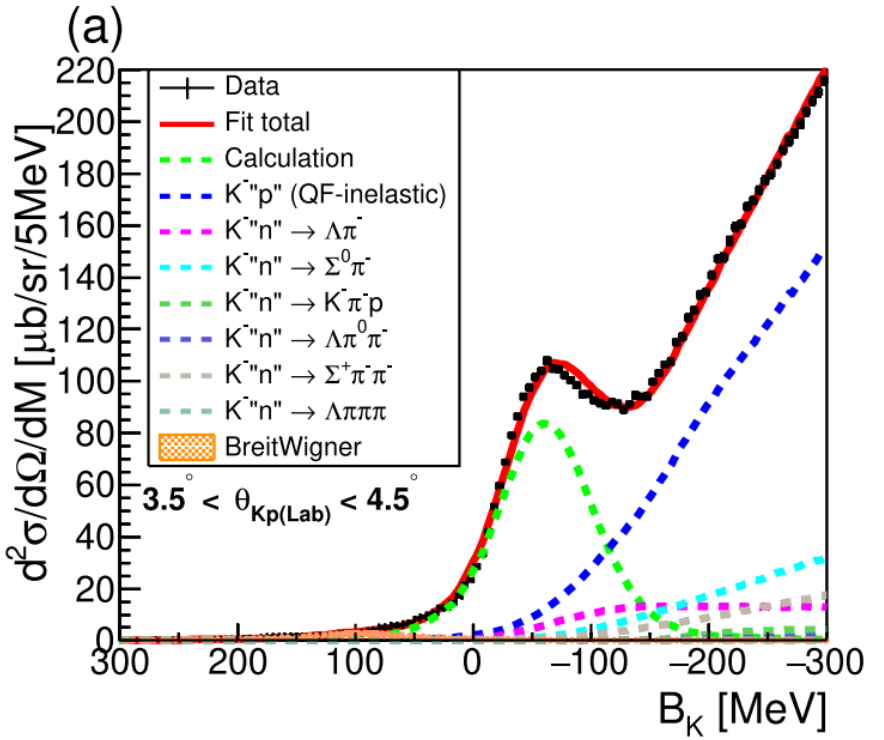


Kaonic nucleus search via inclusive $^{12}C(K^-,p)$ reaction (J-PARC E05)

- $^{12}\mathrm{C}(K^-,p)$ binding energy
  - $B_K = -MissingMass + Mass^{11}B + MassKaon$
  - Optical potential between K^- and the core nucleus
    - $(V_0, W_0) = (-80, -40)$ [MeV] [3]
      (V_0, W_0: real/imaginary part)

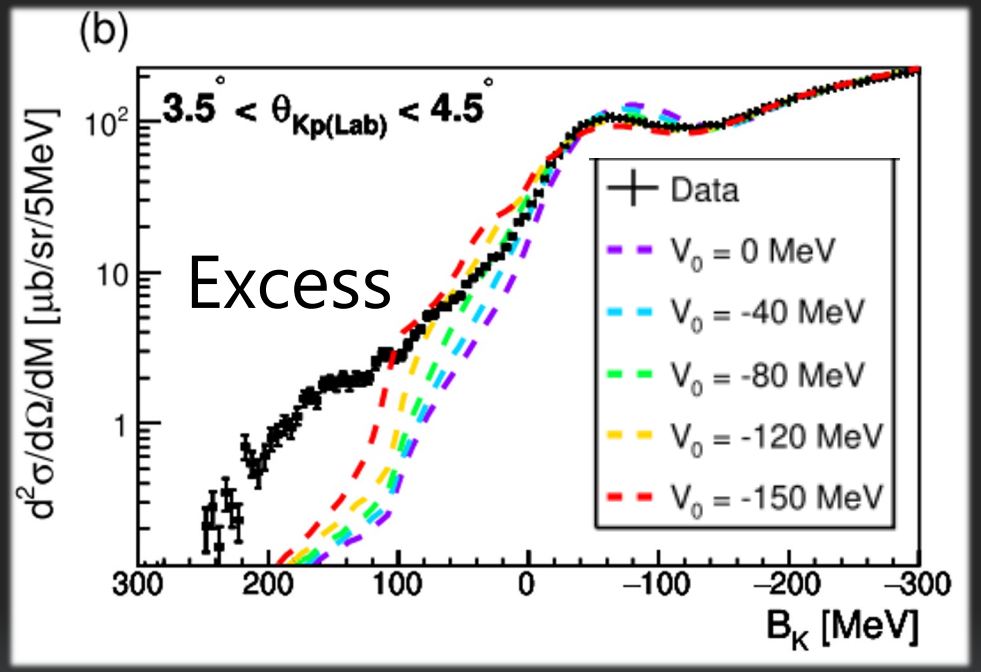
[3] Y. Ichikawa et al., PTEP **2020**, 123D01(2020)

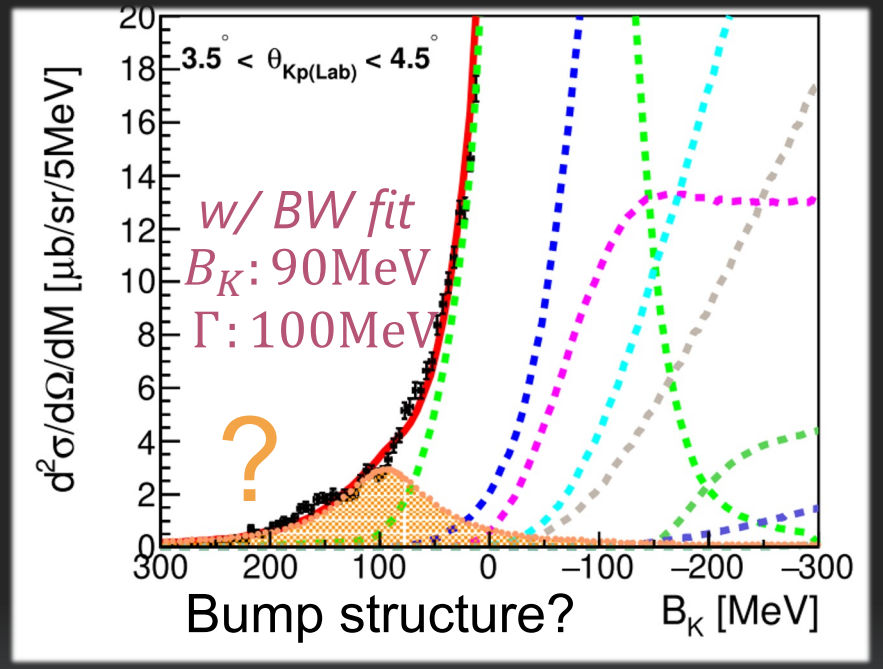


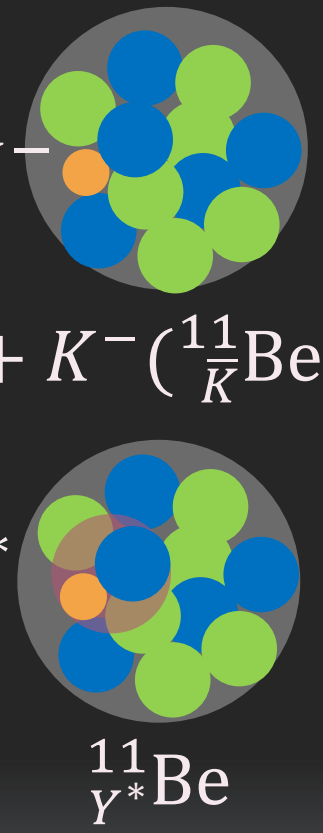


Kaonic nucleus search via inclusive $^{12}C(K^-,p)$ reaction (J-PARC E05)

- Event excess in a deeper energy region of $^{12}\mathrm{C}(K^-,p)$ binding energy
  - Come from a Y^* bound state? (BW fit: B_K: 90MeV, Γ = 100MeV)







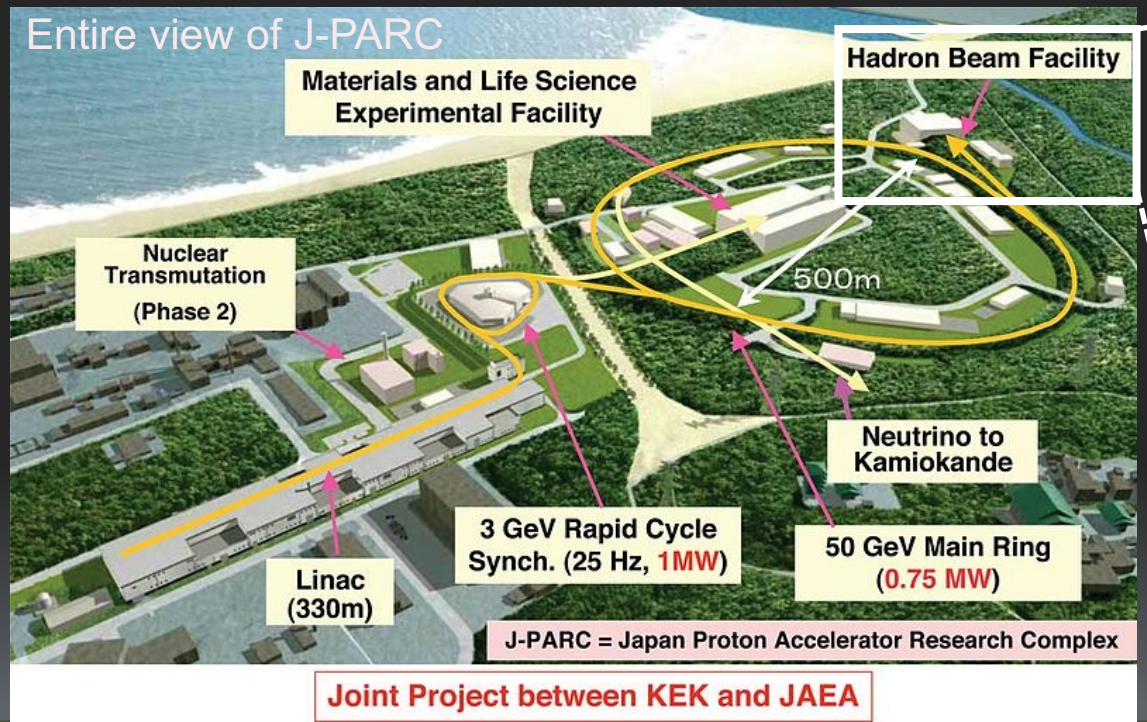
- We can exclusively access this bump structure using data of a recent experiment at J-PARC (E42 experiment)

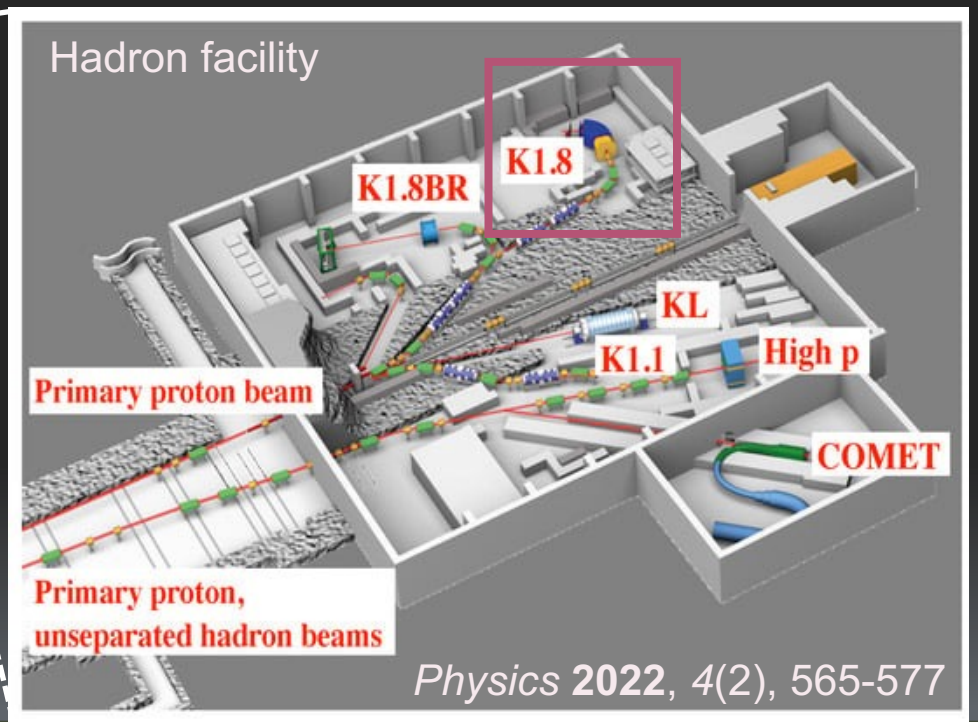
[3] Y. Ichikawa et al., PTEP **2020**, 123D01(2020)

Kaonic nucleus search via exclusive $^{12}C(K^-, p)$ reaction (J-PARC E42)

J-PARC E42 experiment

- **J-PARC** (**J**apan **P**roton **A**ccelerator **R**esearch **C**omplex)
  high energy and high intensity proton beam is available
- Hadron hall
  We can use a variety of secondary beams such as kaon, pion, and so on.





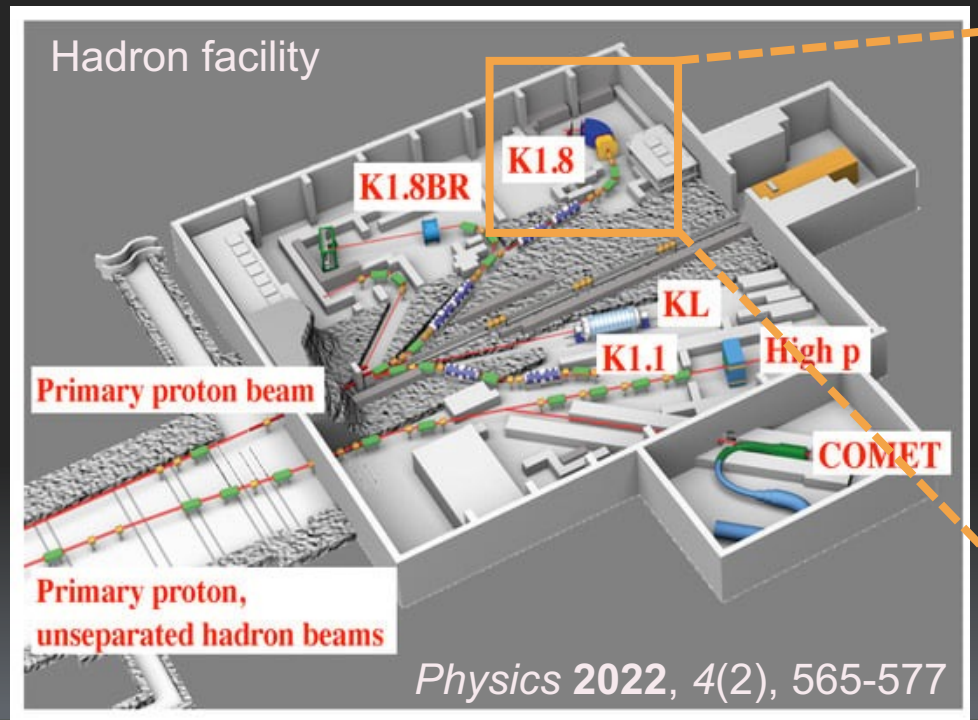
J-PARC E42 experiment

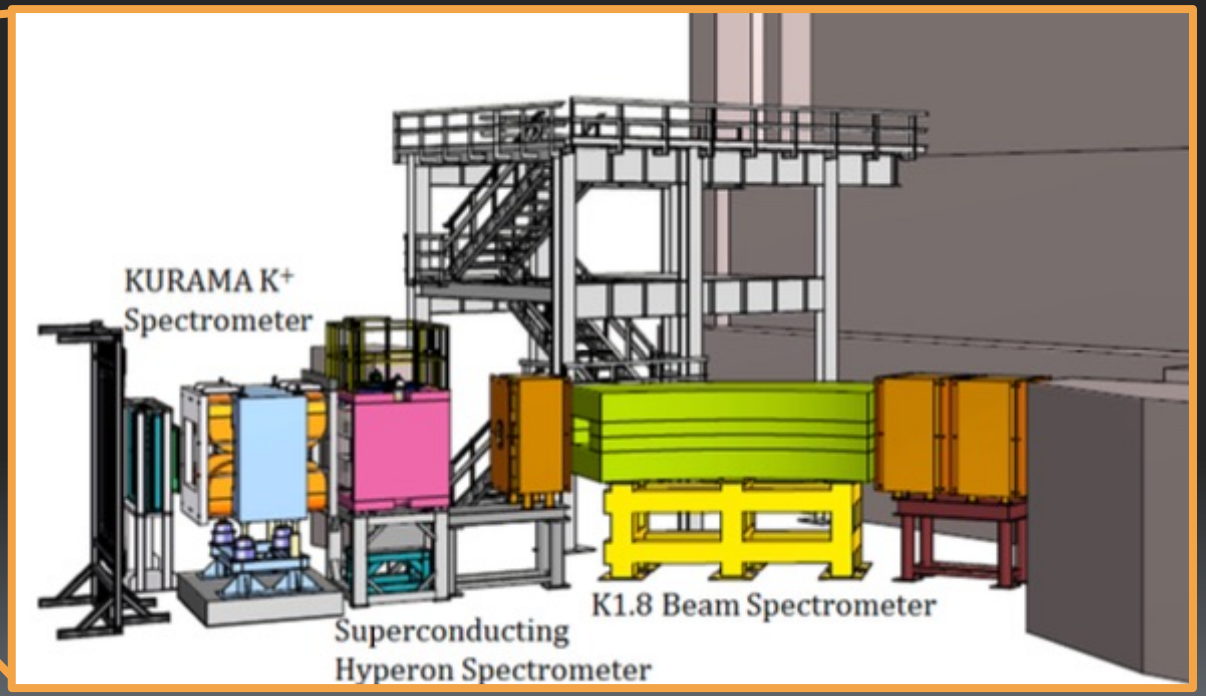
- Hadron hall

  We can use a variety of secondary beams such as kaon, pion, and so on.

- K1.8 beamline

  High-intensity (~10^7 Hz) and high-momentum (~1.8 GeV/c) Kaon beam is available



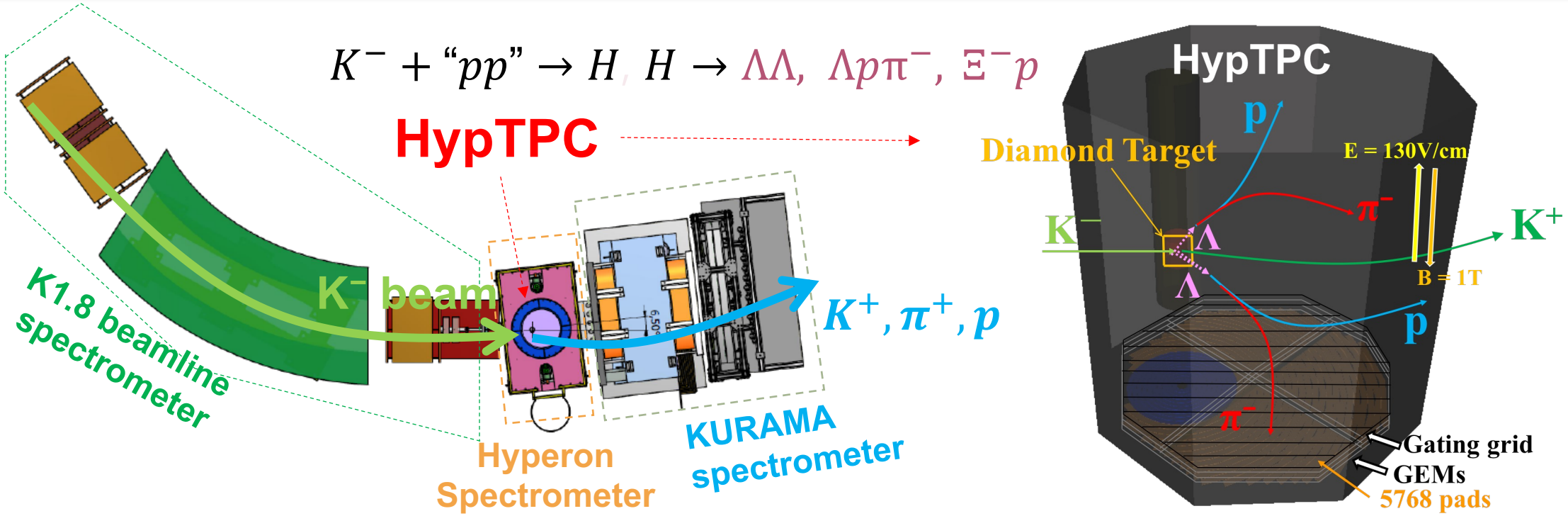


J-PARC E42 experiment

- Invariant mass spectroscopy of H-dibaryon using **HypTPC** (J-PARC E42)

  Completed in 2021

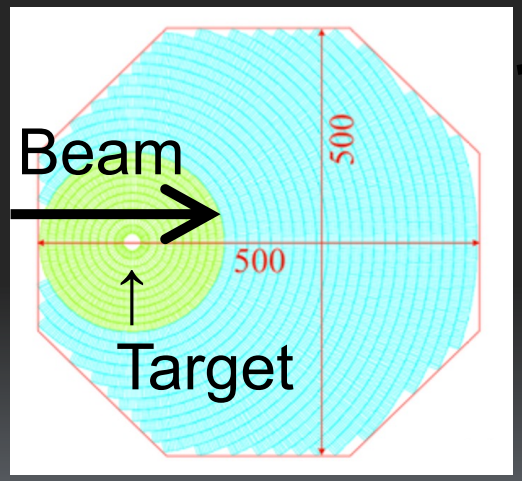
  -1.8 GeV/c Kaon beam on a diamond target

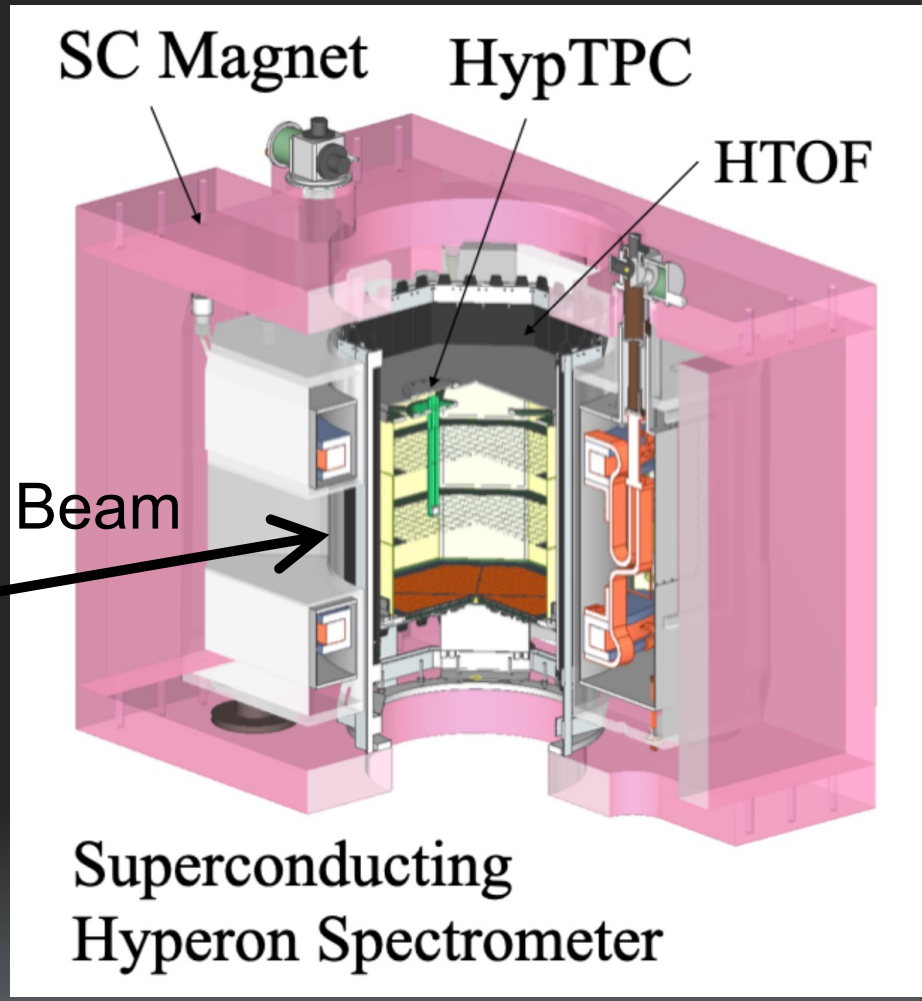


HypTPC

- GEM-based time projection chamber
- ~5700 GEM pads are used
- Observables : Momentum, TOF, Energy deposit

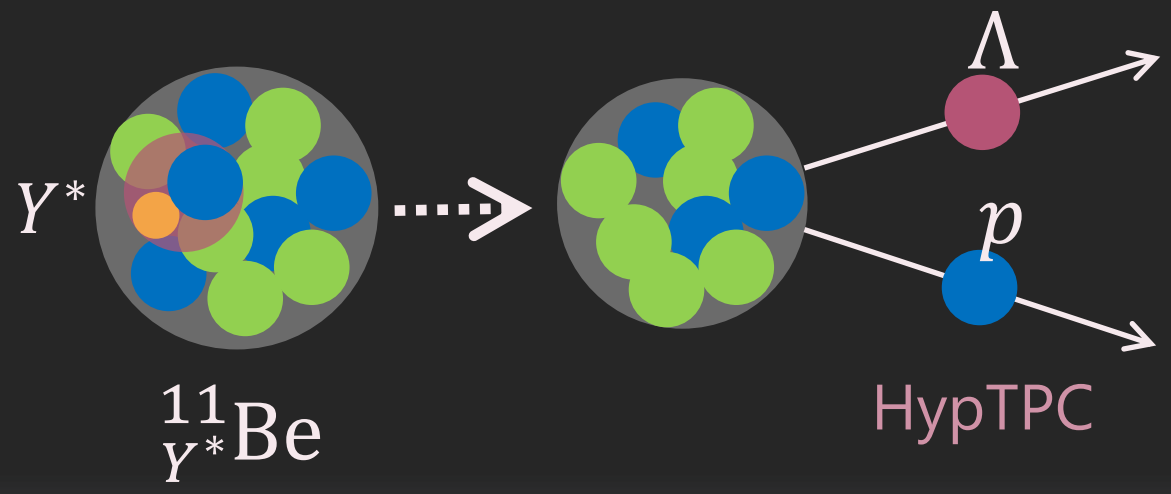
- Large acceptance (~4π) (target installed in TPC)
- High-rate capability (~10^6Hz)
- High resolution (~1 MeV in σ)



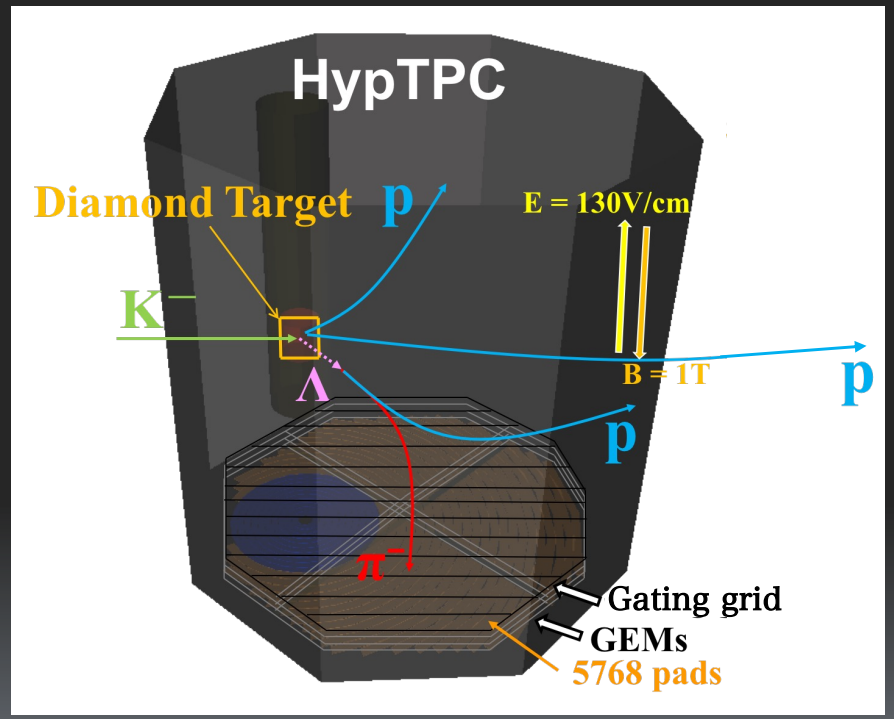


Kaonic nucleus search measuring $^{12}C(K^-, p)$ and decay particles

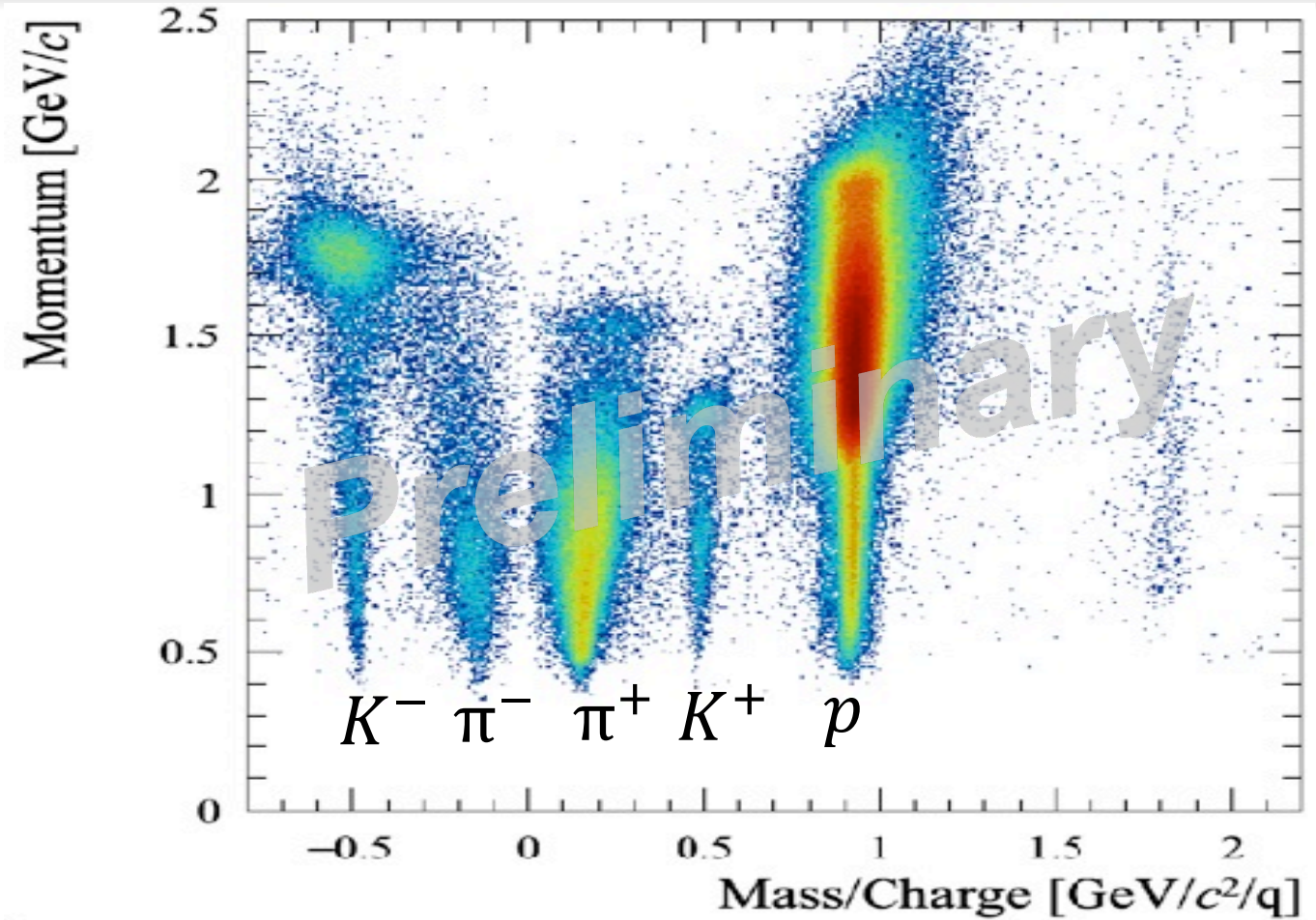
- We can search $\bar{K}$ nucleus via the same $^{12}\mathrm{C}(K^-, p)$ reaction as E05(inclusive)
- Possible to measure decay particles $\Lambda\mathrm{p}$ using Time-Projection chamber, HypTPC
- Possible to observe a clear bump structure with good S/N ratio

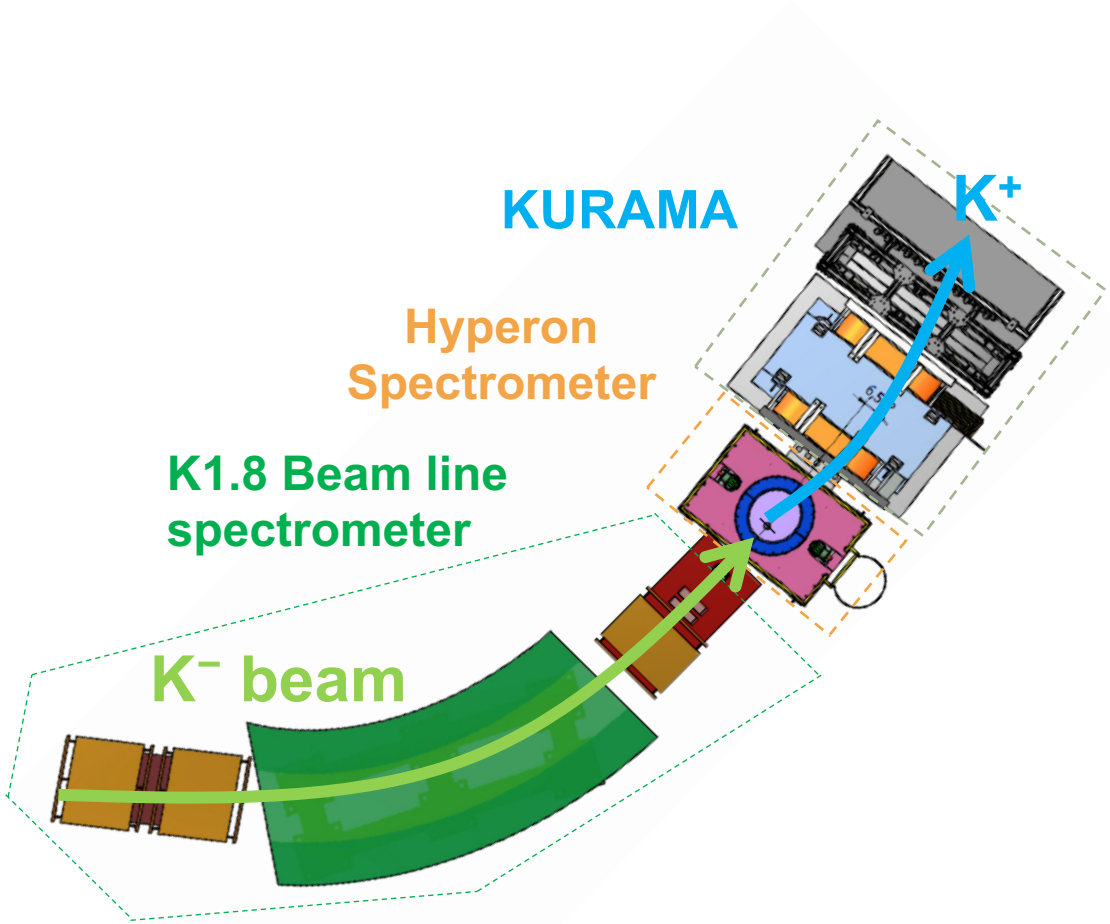


Measurement of $^{12}\mathrm{C}(K^-, p)$ missing mass with $\Lambda\mathrm{p}$ coincidence

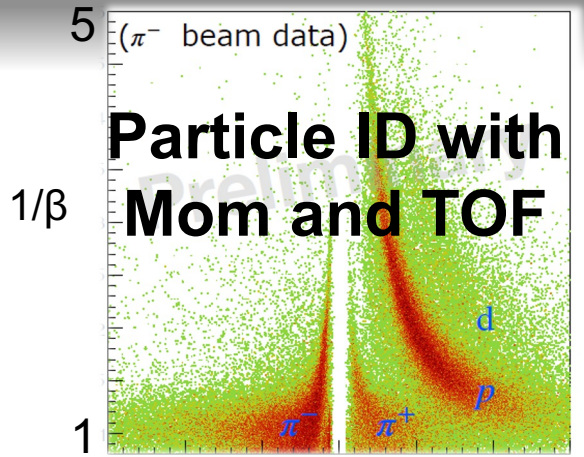


Analysis of KURAMA spectrometer for the forward scattered particles

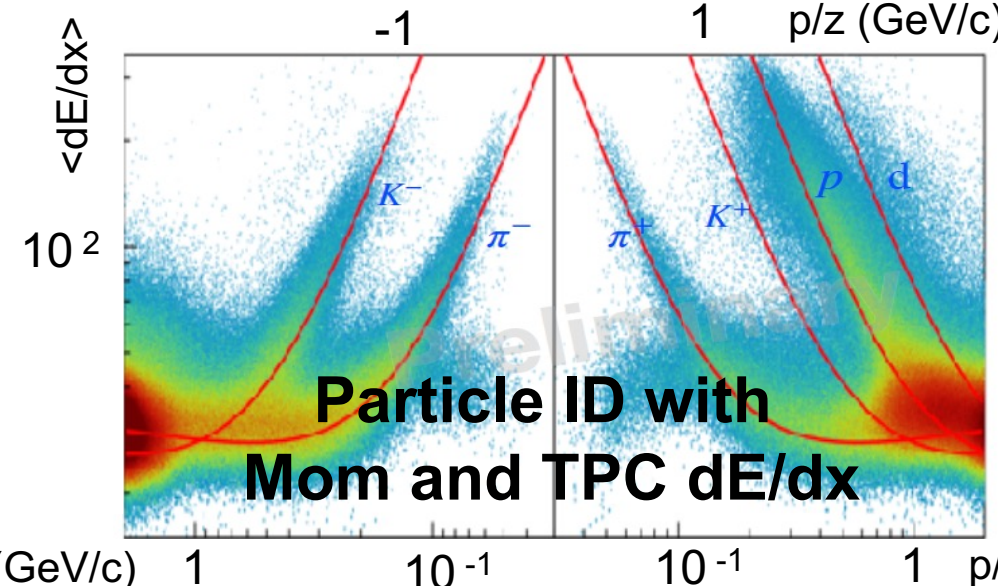




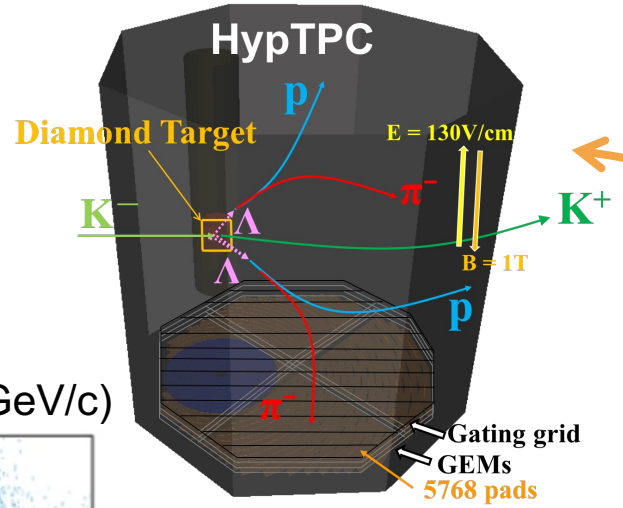
Analysis of Hyperon Spectrometer (HypTPC) for decay particles

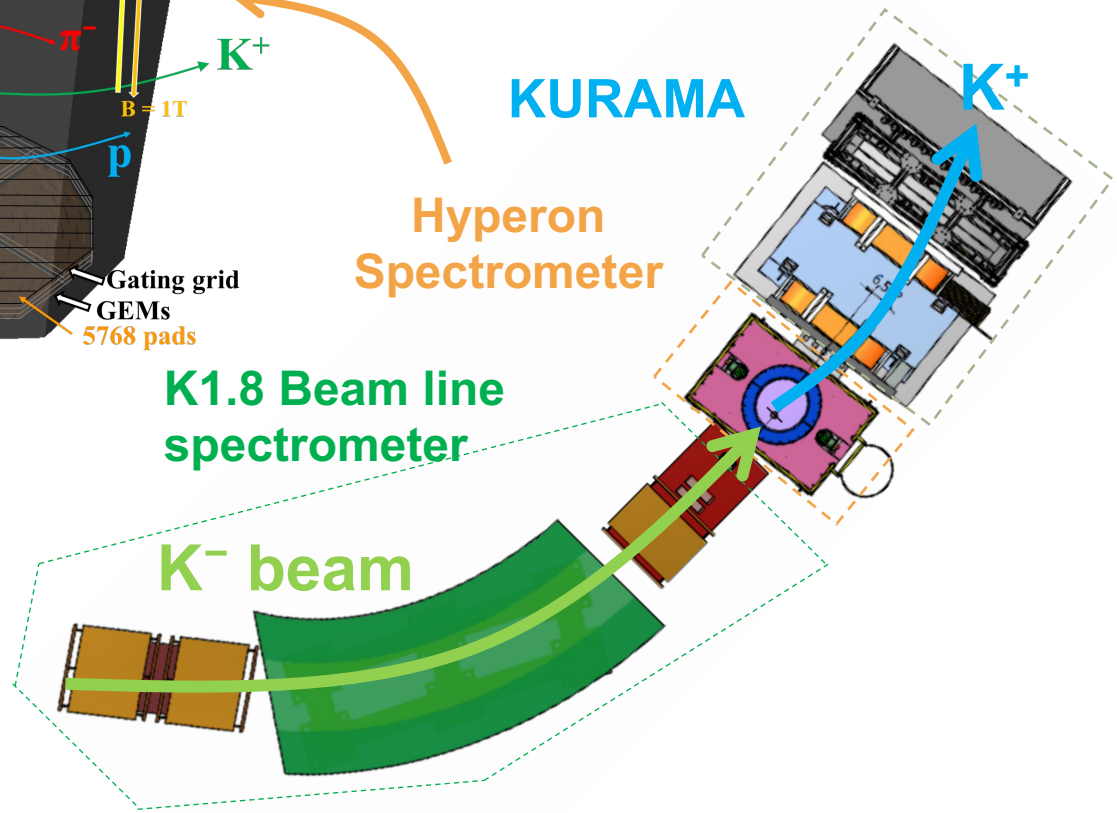


Particle ID with Mom and TOF



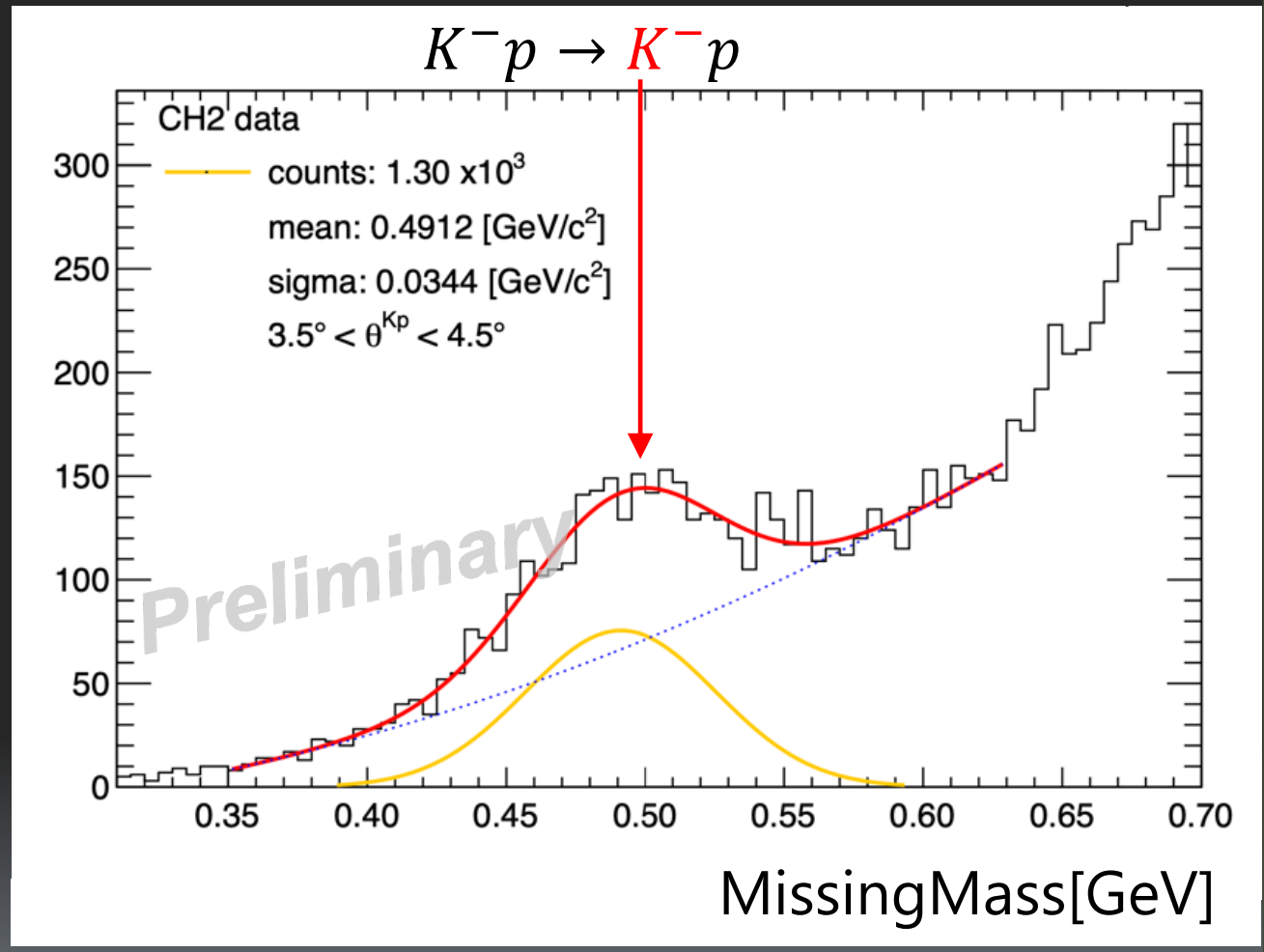
Particle ID with Mom and TPC dE/dx





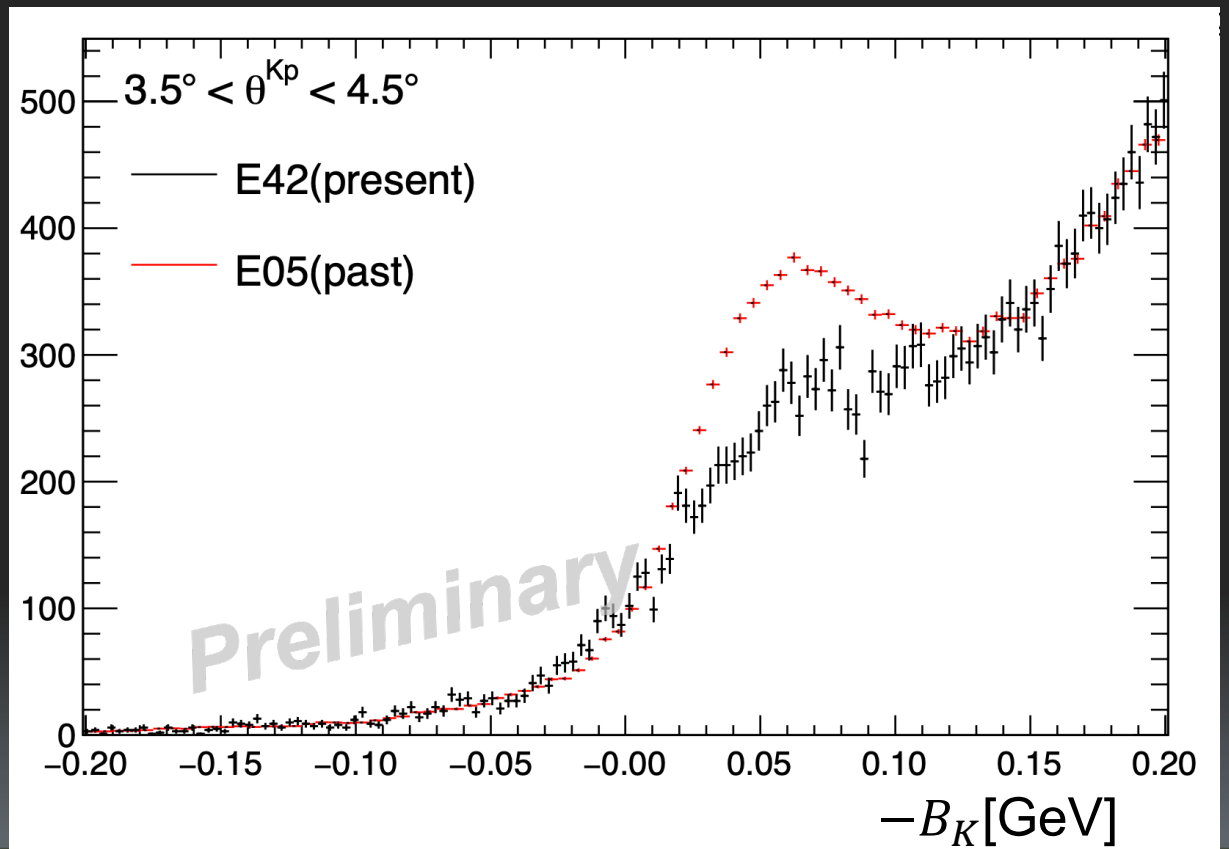
Missing mass of $p(K^-, p)$ reaction

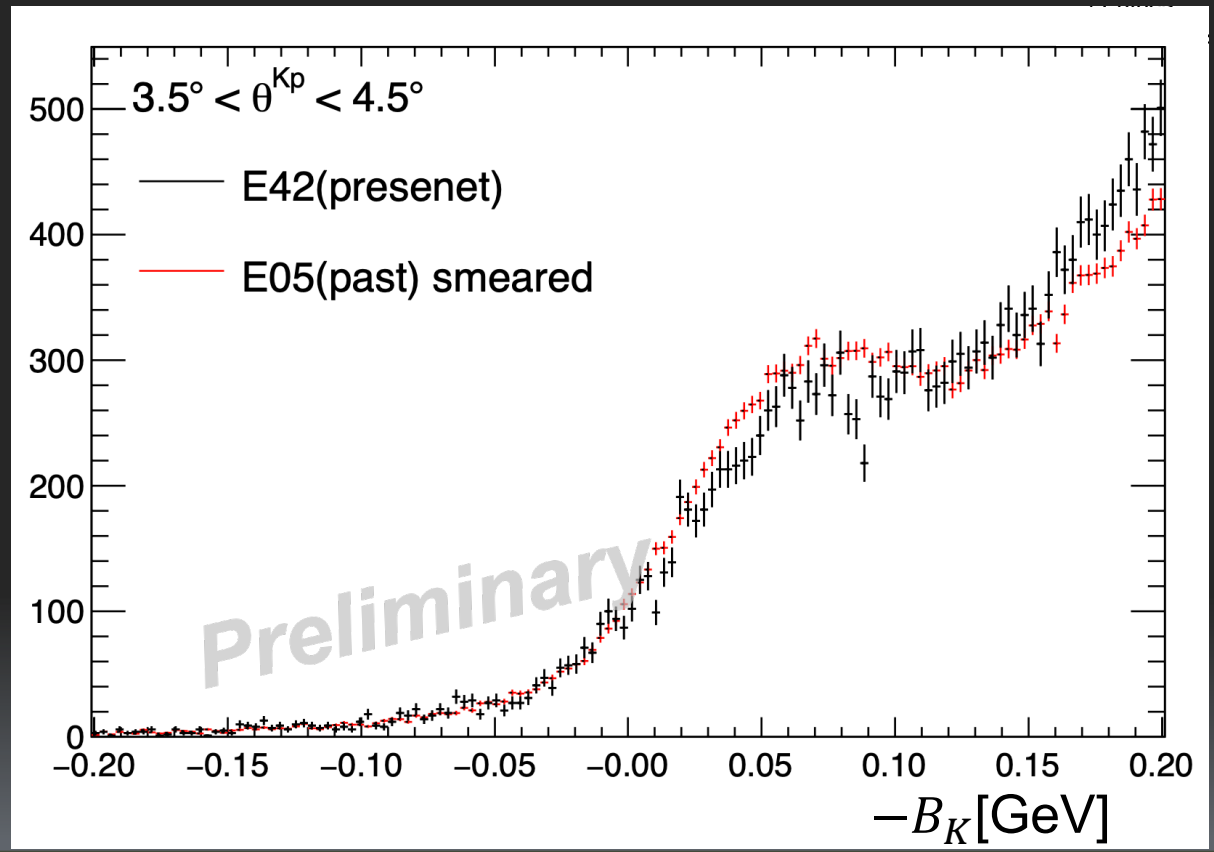
- Fitted with gaussian + quadratic
- Resolution of elastic kaon: 34.4 MeV (σ)
- From this value, we can estimate resolution for B_K of $^{12}C(K^-, p)$ around 0 MeV to be 22 MeV (σ)



Inclusive spectrum of $^{12}C(K^-,p)$ reaction

- Binding energy of $^{12}C(K^-,p)$ of E05data (scaled) and E42 data
- E05 data smeared with E42 resolution (22 MeV in σ)

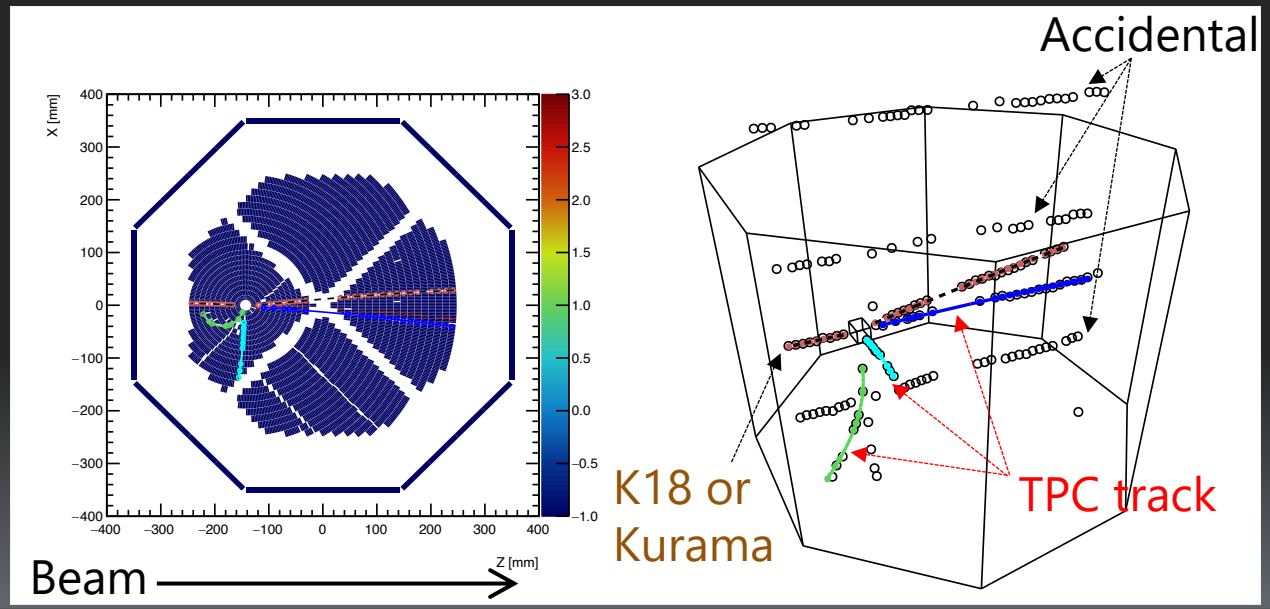


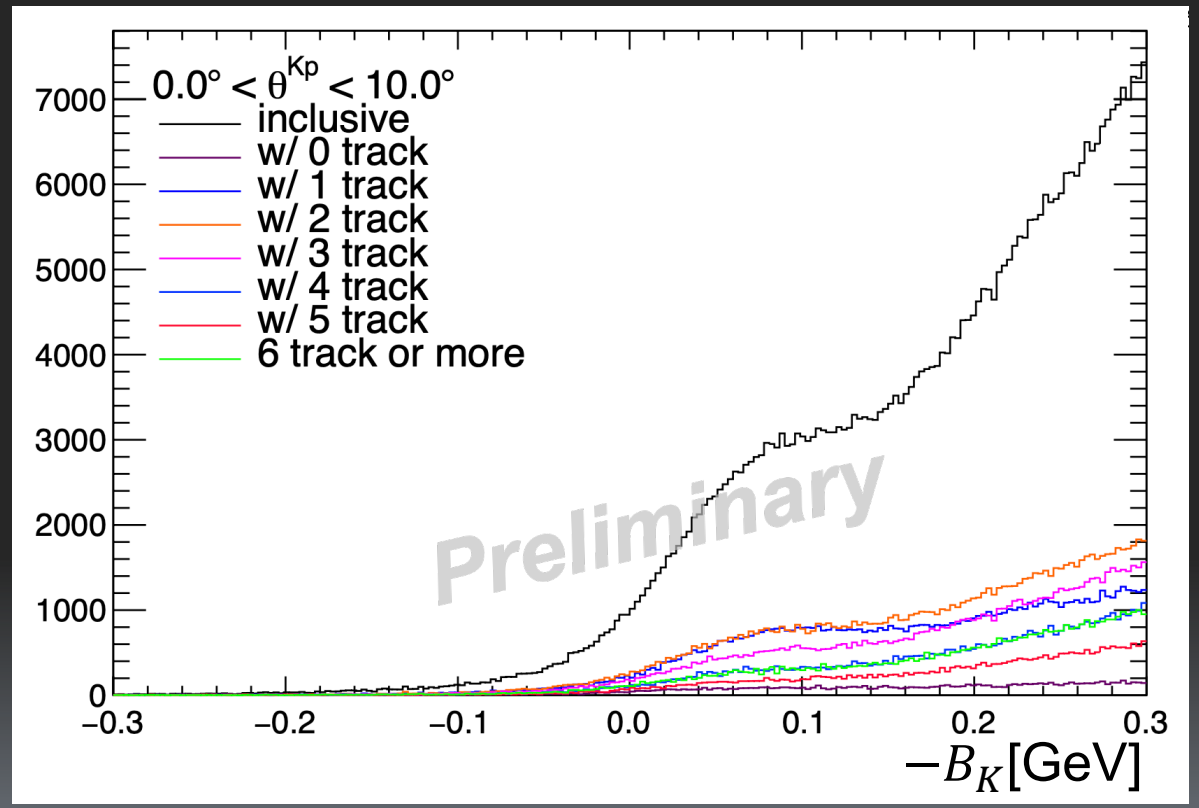


Exclusice spectrum of $^{12}C(K^-, p)$ with request for TPC tracking

- Binding Energy
  - Beam Kaon and Scattered proton are requested
  - $0° < \theta^{kp} < 10°$

- TPCTrack = trackTotal – trackBeam
  – trackKurama – trackAccidental

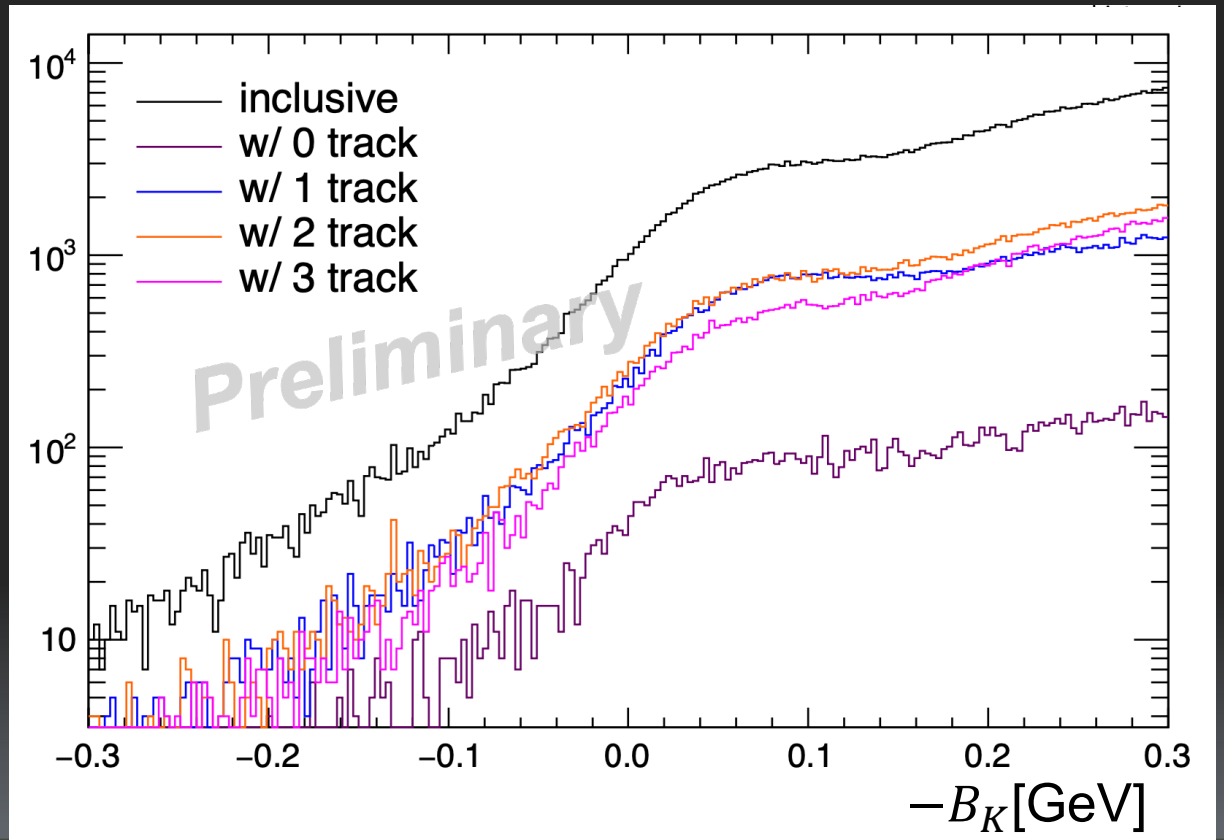


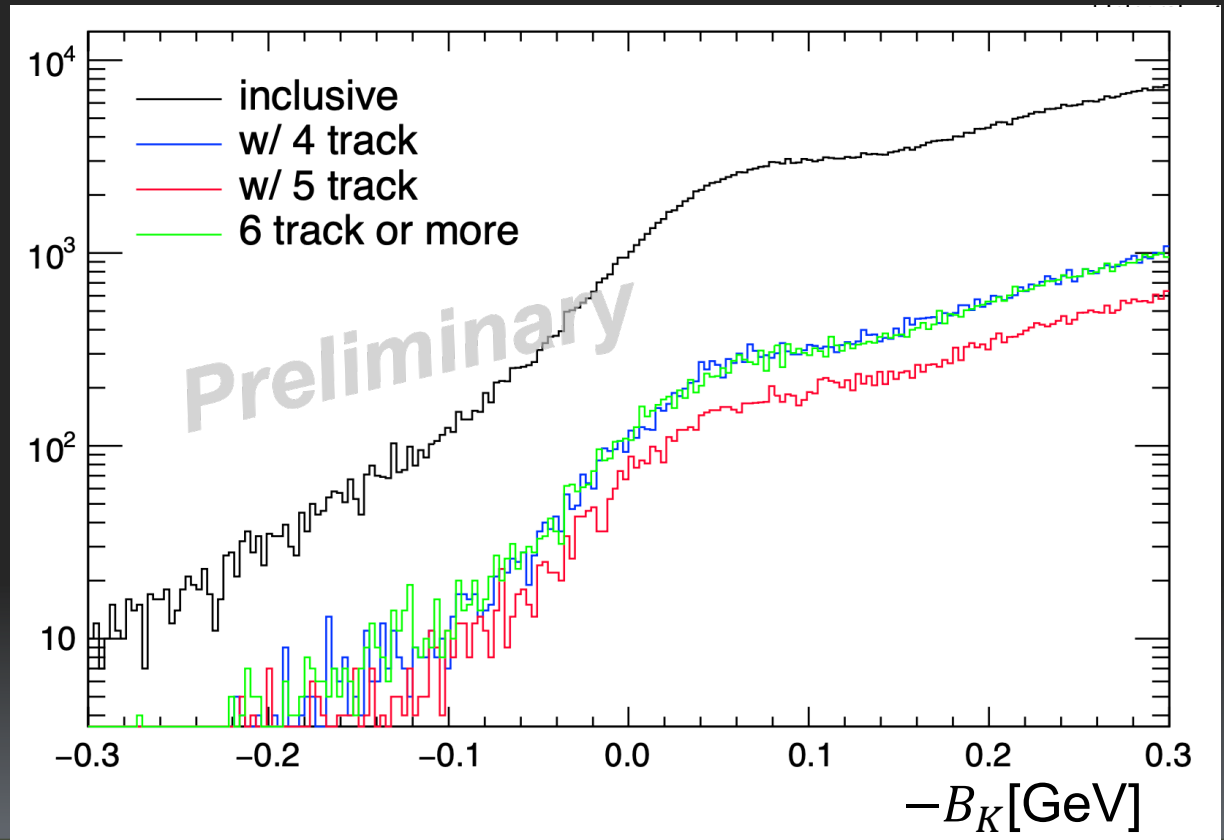


Exclusice spectrum of $^{12}C(K^-, p)$ with request for TPC tracking

- Binding Energy
  - Beam Kaon and Scattered proton are requested
  - $0° < \theta^{kp} < 10°$

In bound region, 2 or 3 tracks can be seen more than others. For further discuss, it's necessary to require PID or momentum.





Summary

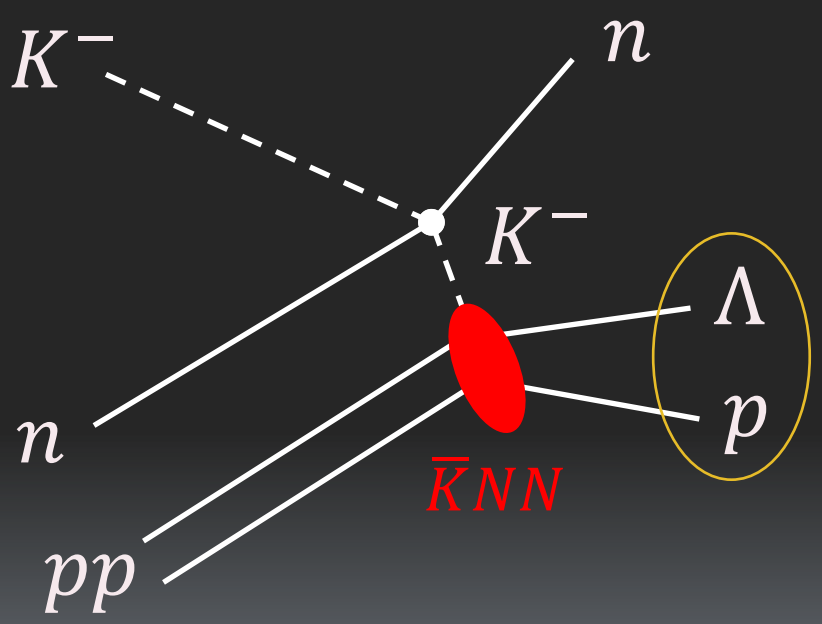
- $\overline{K}N$ interaction and $\overline{K}N$ bound system are still unclear
- Inclusive spectroscopy via $^{12}\mathrm{C}(K^-, p)$ (E05 experiment)
  - Determined optical potential between K^- and the core nucleus
  - Observed event excess in deeper region of binding energy

- Exclusive spectroscopy via $^{12}\mathrm{C}(K^-, p)$ using HypTPC (E42 experiment)
  - Was completed in 2021
  - Can access event excess measuring decay particle with HypTPC
  - Analysis is ongoing
    - Energy resolution of B_K was ~20 MeV estimated by $p\,(K^-, p)$
    - Comparison of B_K between this experiment and past experiment
    - Exclusive spectrum with request for multiplicity of tracks in TPC
  - Further analysis like decay particle identification and momentum measurement is ongoing.

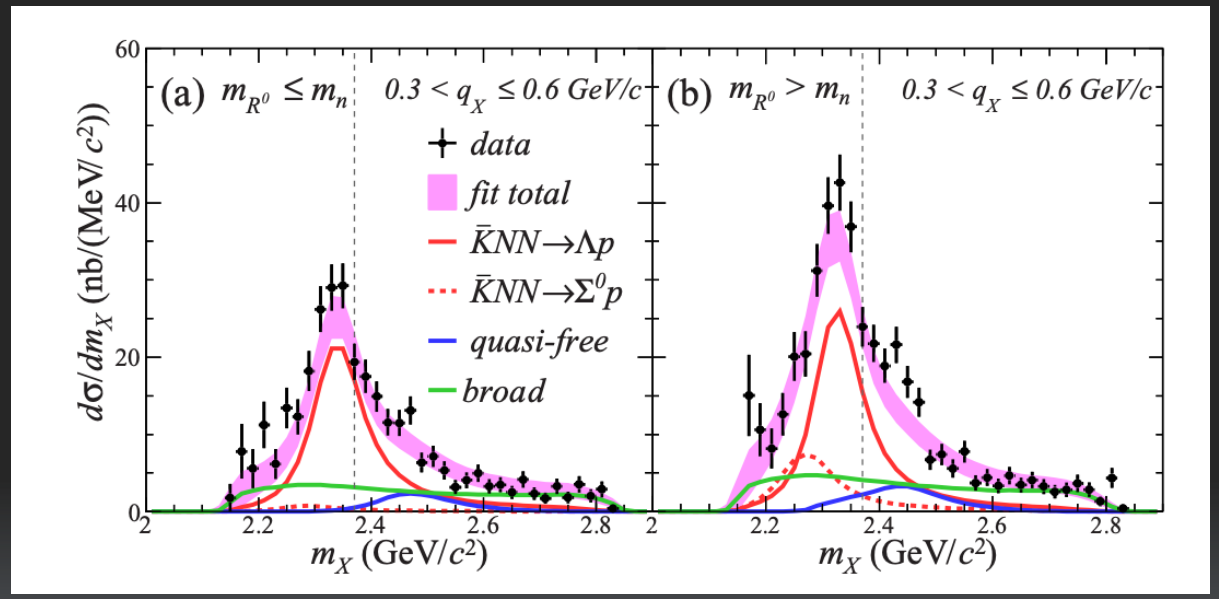
Backup slides

$\bar{K}NN$ Search via $^3\mathrm{He}(K^-, \Lambda p)n$ (J-PARC E15)

- Clear bump structure was observed.
  - Lightest Kaonic nucleus
  - $B_K = 42 \pm 3\ ^{+3}_{-4}$ MeV $(B_K = m_K + A \cdot M_N - M_{KA})$
  - Decay width $\Gamma_K = 100 \pm 7\ ^{+19}_{-9}$ MeV



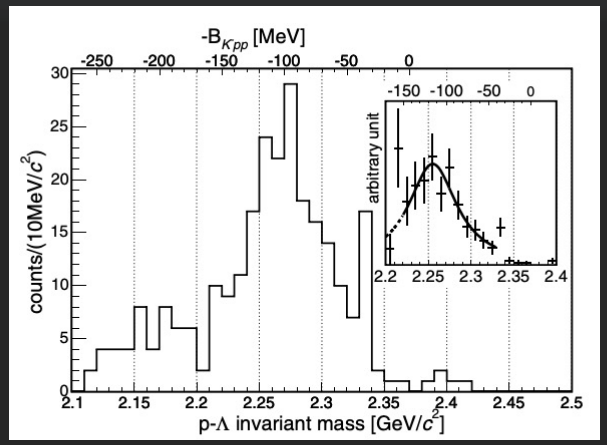
Invariant mass

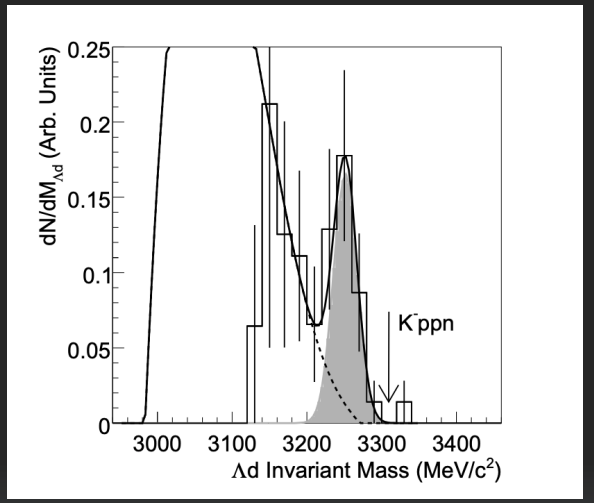


T. Yamaga *et al.* (J-PARC E15 Collaboration)
Phys. Rev. C **102**, 044002 (2020)

Suggestion of Existence of $\bar{K}NNN, \bar{K}NNNN, \ldots$

- $\bar{K}NN$ was found also in FINUDA experiment
  - Back-to-back Λp pair
  - Invariant mass is much lower than Λp
- $\bar{K}NNN, \bar{K}NNNN$ were also found
  - Back-to-back Λd and Λt pairs
  - Smaller binding energy than that of $\bar{K}NN$
- Theoretical suggestion
  - $\bar{K}NNN, \bar{K}NNNN, \bar{K}NNNNNN$ [1]
  - Heavier states like $^{256}\mathrm{Pb} + K^-$ have large B_K but large Γ_K[2]





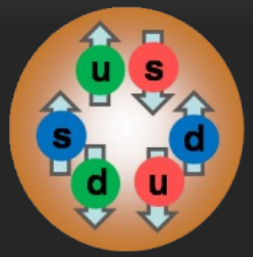
M. Agnello *et al.* (FINUDA Collaboration) Phys. Rev. Lett. **94**, 212303

M. Agnello *et al.* (FINUDA Collaboration) Eur. Phys. J. A 33, 283–286 (2007)

[1] S. Ohnishi, W. Horiuchi, T. Hoshino, K. Miyahara, and T. Hyodo, Phys. Rev. C **95**, 065202

[2] J. Hrtánková and J. Mareš, Phys. Rev. C **96**, 015205

Search for H-dibaryon

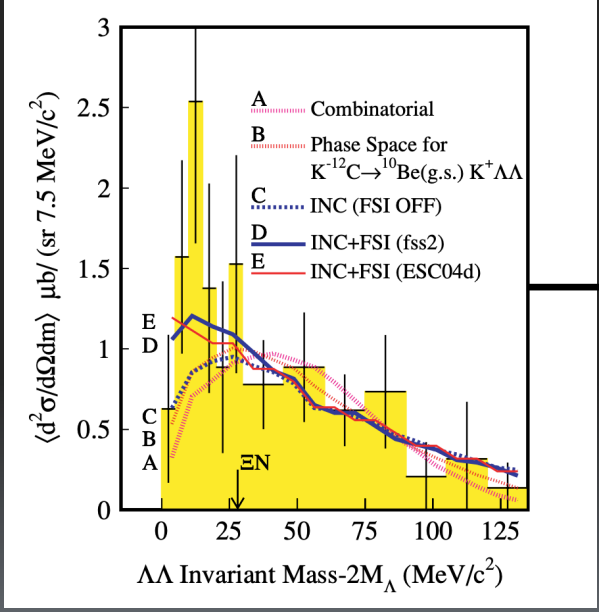


- **H-dibaryon** : exotic hadron, six quark state of uuddss (I=0, J=0)
- Bound or resonance? Mass close to $\Lambda\,\Lambda$ or ΞN threshold?
  - Very meaningful because this state is deeply related to $\Lambda\,\Lambda - \Sigma\Sigma - \Xi N$ coupling channel
  - Lattice QCD calculation → near ΞN threshold
- History of H-dibaryon search

KEK-PS E522

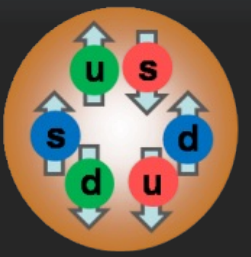
statistics & resolution not enough

C. J. Yoon *et al.* Phys. Rev. C **75**, 022201(2007)



1977	Deeply-bound di-hyperon predicted by R. Jaffe
1980-2000	No evidence for the deeply-bound H from KEK, BNL, and CERN experimental efforts by more than 80 MeV
2001	Mass constraint from observation of ${}^{6}_{\Lambda\Lambda}$He (E373)
1998,2007	Enhanced $\Lambda\Lambda$ production near threshold was reported from E224 and E522 at KEK-PS.
2011	LQCD calculations predict the H-dibaryon near $m_{\Lambda\Lambda}$
2013-2015	No evidence for $H \to \Lambda p \pi^-$ and $H \to \Lambda\Lambda$ in high-energy e^+e^-, pp and AA experiments
2021	LQCD calculations point to the mass the H-dibaryon very close to ΞN threshold ($m_\pi \approx 146$ MeV)
2021	**J-PARC E42 has successfully completed with HypTPC.**

Search for H-dibaryon



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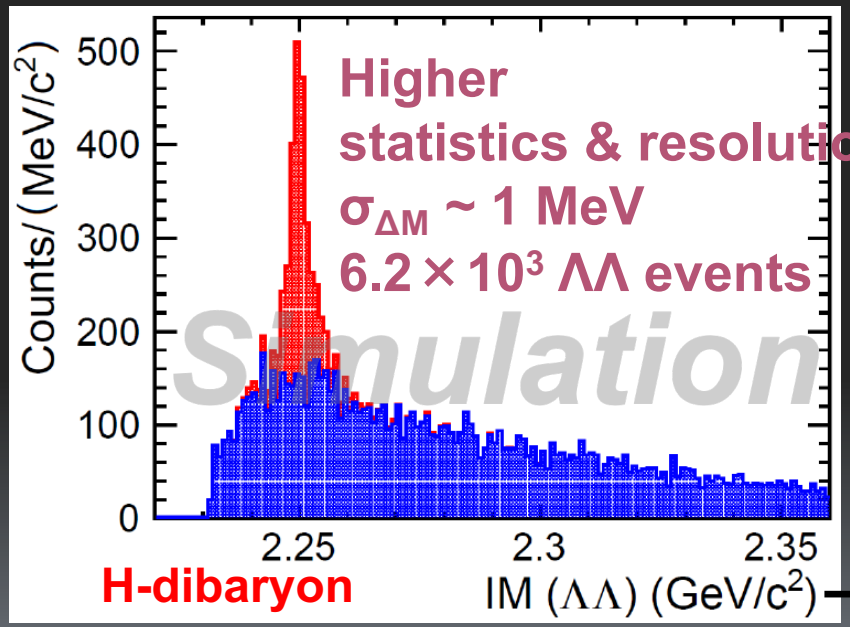

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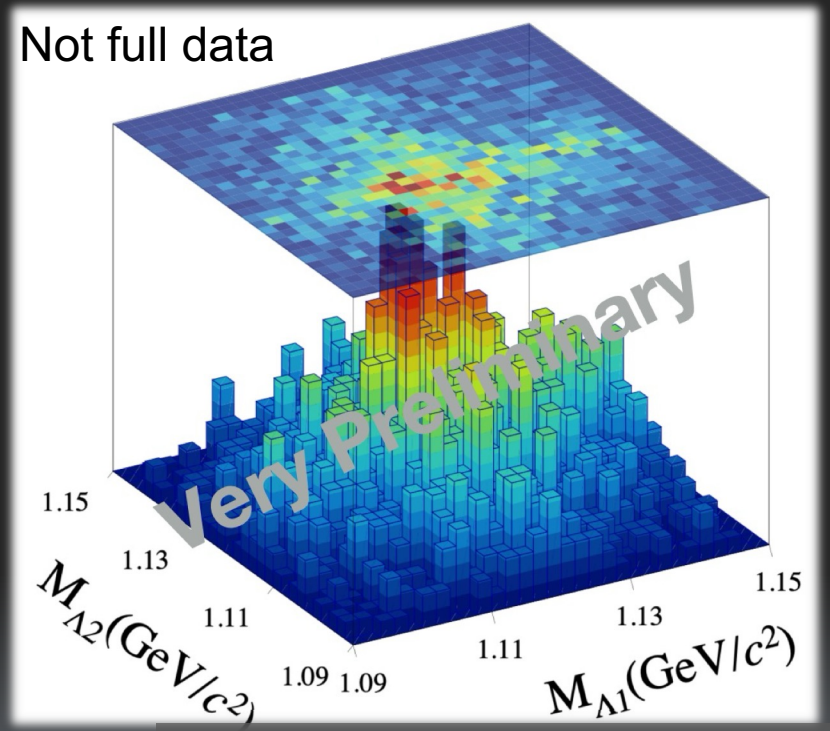
ΛΛ reconstruction

3000 ΛΛ events are reconstructed (not full data)



Summary of past experiments

	KEK E224	KEK E522
Beam K^-	$p_{(K^-)}$ = 1.65 GeV/c	$p_{(K^-)}$ = 1.66 GeV/c
$p_{(K^+)}$ [GeV/c]	0.95<$p_{(K^+)}$ <1.3	0.9<$p_{(K^+)}$ <1.3
dσ/dΩ（ΛΛ）	7.6 μb/sr	12.8 μb/sr
ΛΛ yield	35 events	68 events

Comparison with expected yield

$p_{(K^+)}$ [GeV/c]	**0.95<$p_{(K^+)}$ <1.3**		**0.5 < $p_{(K^+)}$**
Assumed dσ/dΩ(ΛΛ)	7.6 μb/sr	12.8 μb/sr	
Expected ΛΛ	337 events	570 events	
Expected ΛΛ yield	520 events	880 events	
Measured ΛΛ yield	1,390 events		3,030 events

More than expected! We will open H-dibaryon box soon!

HypTPC enables investigation in many other topics

- We are currently working on the following topics using E42 data;
  1. Kaonic nucleus search via exclusive $^{12}\mathrm{C}(K^-, p)$ reaction
  2. Measurement of Ξ-nucleus optical potential via $^{12}\mathrm{C}(K^-, K^+)$
  3. Polarization measurement of Ξ and $\Xi^*(1535)$ via $\mathrm{p}(K^-, K^+)\Xi/\Xi^*$
  4. Study of ChSB effect by measurement of $K^*(892)$ vector mass via $^{12}\mathrm{C}(K^-, p)$

Hopefully, there may be many other byproducts!

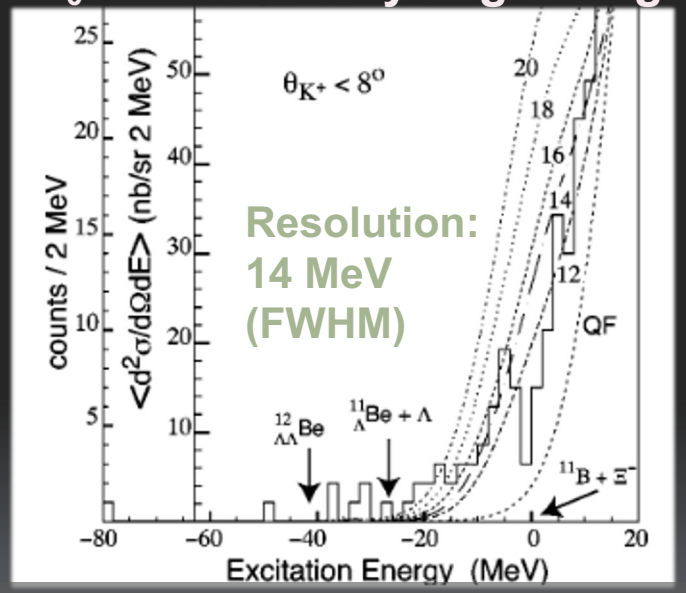
Byproduct.

Measurement of Ξ^--*nucleus optical potential via* $^{12}\mathrm{C}(K^-, K^+)$

- Many experiments have been studying Ξ^--nucleus interaction but its imaginary part havs not been well determined yet. Difficult to determine from the inclusive measurement.

BNL E885

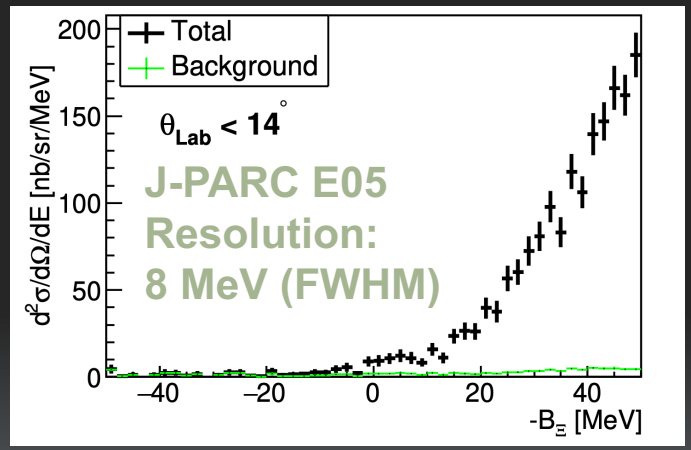
^{12}C(K$^-$, K$^+$) inclusive spectrum
→ V_0^{Ξ} ~ -14 MeV by neglecting W_0^{Ξ}



P. Khaustov et al., PRC 61, 054603 (2000)

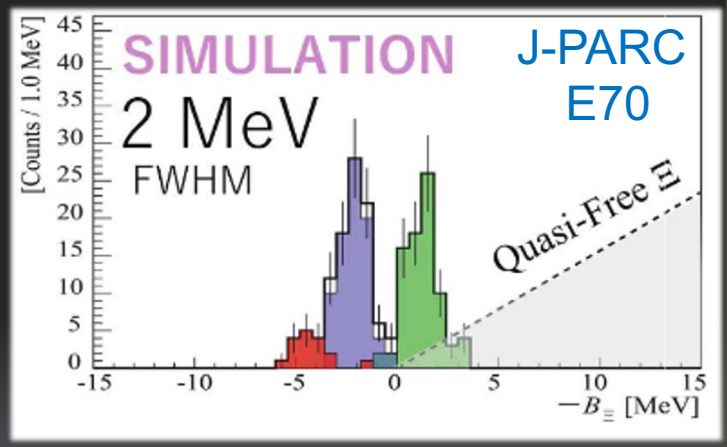
J-PARC E05/E70

^{12}C(K$^-$, K$^+$) inclusive spectrum with wide B_{Ξ} range is taken.



Y. Ichikawa *et al.*, PTEP, to be published

Best resolution 2 MeV will be achieved in E70



T. Gogami *et al.*, EPJ Web Conf. 271, 1102 (2022).

Byproduct.

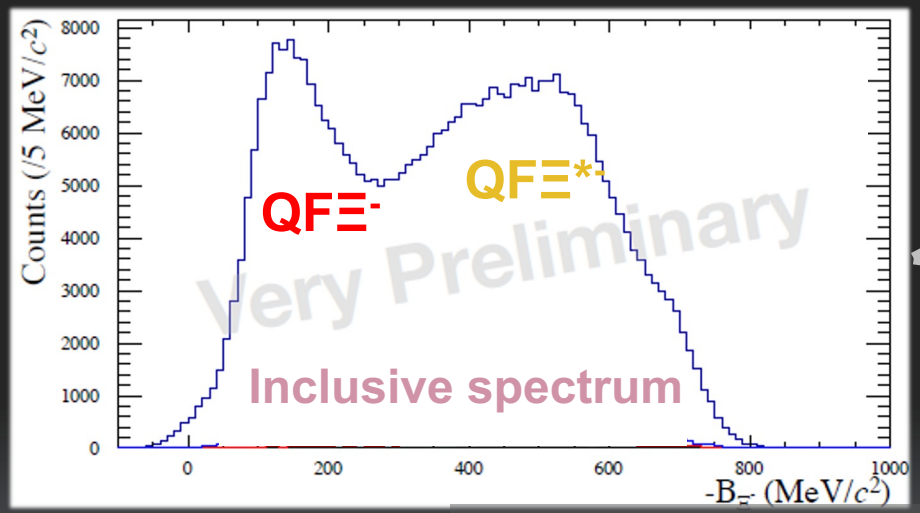
Measurement of Ξ^--*nucleus optical potential via* $^{12}C(K^-, K^+)$

- E42 experiment can investigate

  Ξ^- escape or $\Xi^- p \rightarrow \Lambda\Lambda$ conversion spectra

  → Sensitive to the imaginary part of the potential!

$^{12}C(K^-, K^+)$ inclusive spectrum

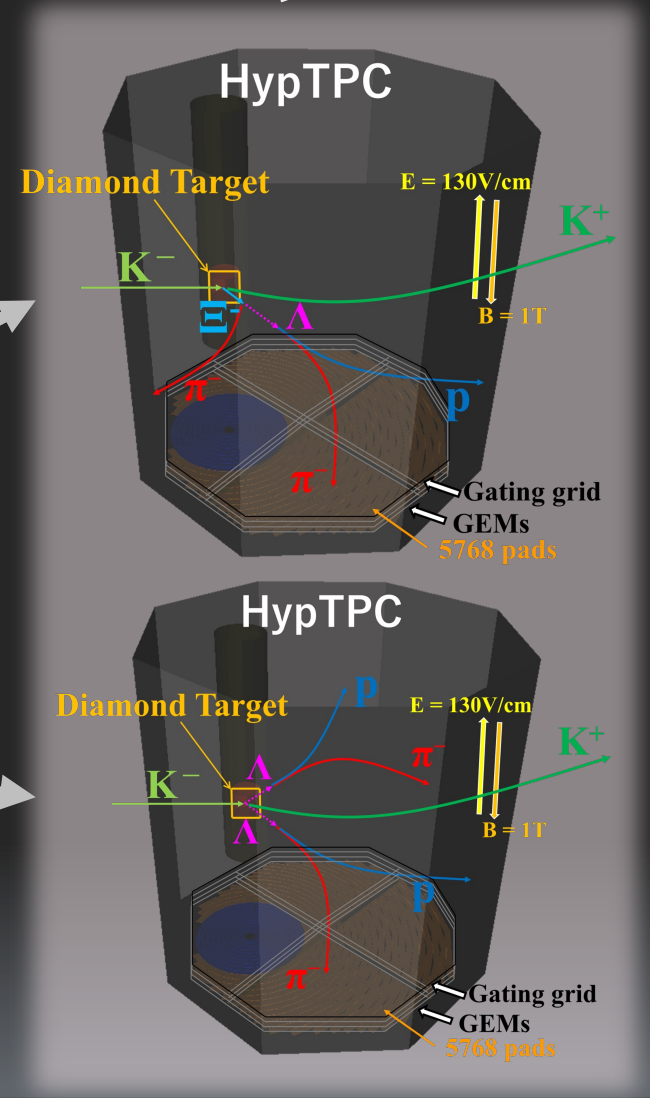


QFΞ^-: K^- "p"→ Ξ^- K^+

QFΞ^*: K^- "p"→Ξ^*(1535) K^+
K^- "p"→Ξ π K^+

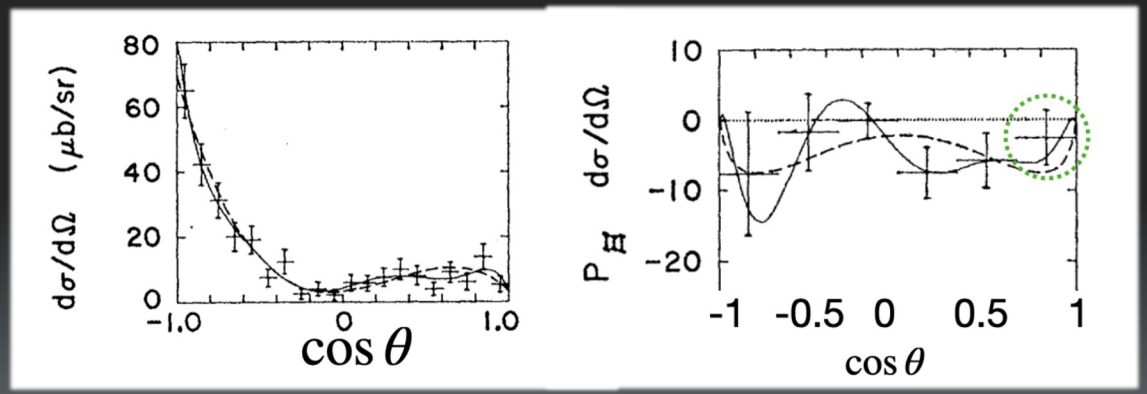
Ξ^- escape spectrum

$\Xi^-p\rightarrow\Lambda\Lambda$ conversion spectrum

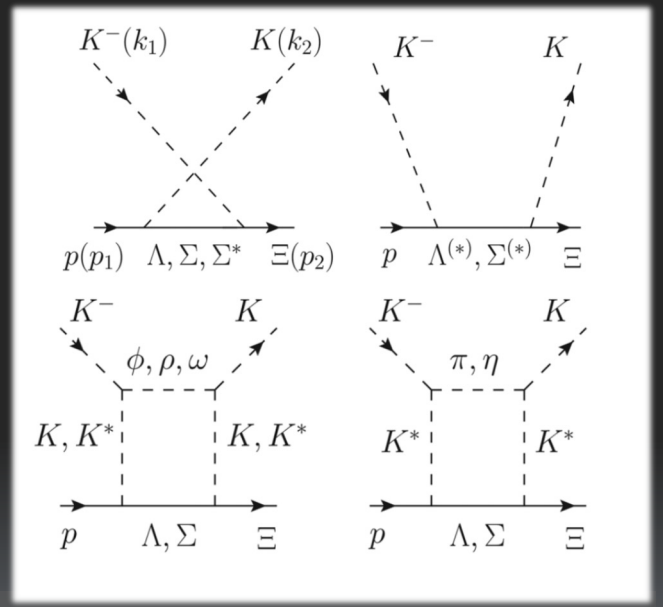


Polarization measurement of Ξ and $\Xi^*(1535)$ via $p(K^-, K^+)\Xi/\Xi^*$

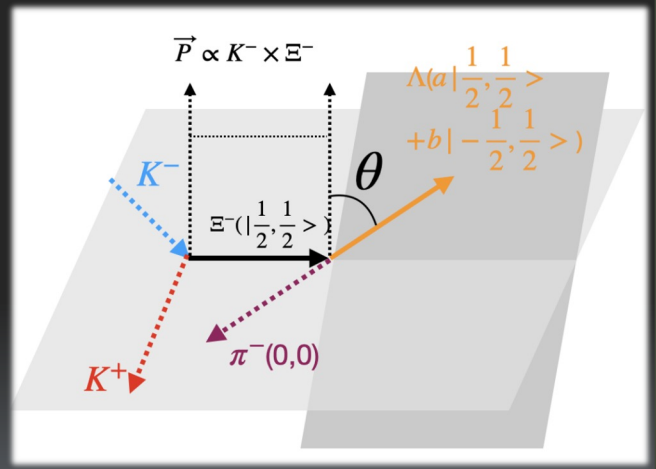
- Some "bump" structures in forward region of $p(K^-, K^+)\Xi^-$ with existing data [4]
- Accounted for by significant contribution from s-channel Λ(2100, 7/2-) and Σ(2300, 7/2+) [5]
- Polarization study is required to investigate the spin structure
- E42 can approach cosθ>0.83 region.
  - Decay amplitude → angular distribution
  - Angular distribution → polarization



[4] G. Burgun *et al.*, Nucl. Phys. B **8**, 447 (1968)



[5] S.H., Kim *et al.*
Phys. Rev. C **107**, 065202(2023)

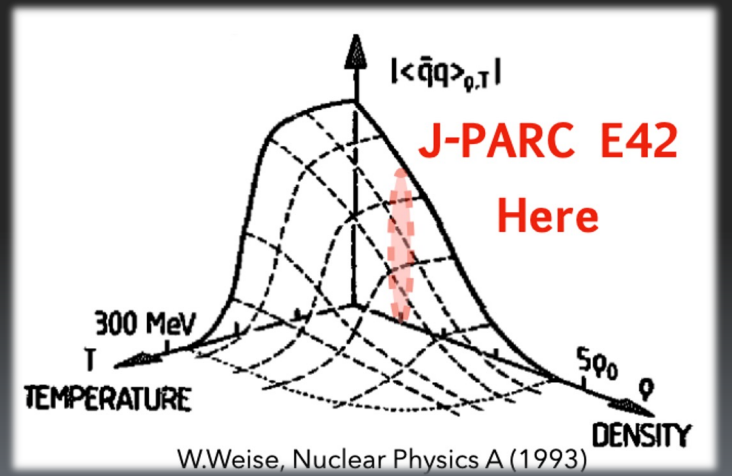


Study of ChSB effect by measuring $K^*(892)$ vector mass via $^{12}\mathrm{C}(K^-, p)$

- Chiral symmetry is believed to be partially restored in nuclear medium
- $K^*(892)$ are suitable for studying possible in-medium modification of mass because of smaller width of the mass than other meson candidates

- HypTPC can observe $K^*(892)$ by reconstructing $K_s^0 \rightarrow \pi^+\pi^-$ and finally $K^*(892) \rightarrow K_s^0\pi^-$

$J^{PC} = 1^{--}$		$J^{PC} = 1^{++}$
$\rho(775)$ ~ 147 MeV/c	⟷	$a_1(1260)$ ~ 250 MeV/c
$\omega(782)$ ~ 8.5 MeV/c	⟷	$f_1(1285)$ ~ 24 MeV/c
$\phi(1020)$ ~ 4.2 MeV/c		
$K^*(892)$ ~ 50 MeV/c	⟷	$K_1(1270)$ ~ 90 MeV/c



W.Weise, Nuclear Physics A (1993)